Idaho National Laboratory

Predicting Ductile Crack Growth in Engineered Structures

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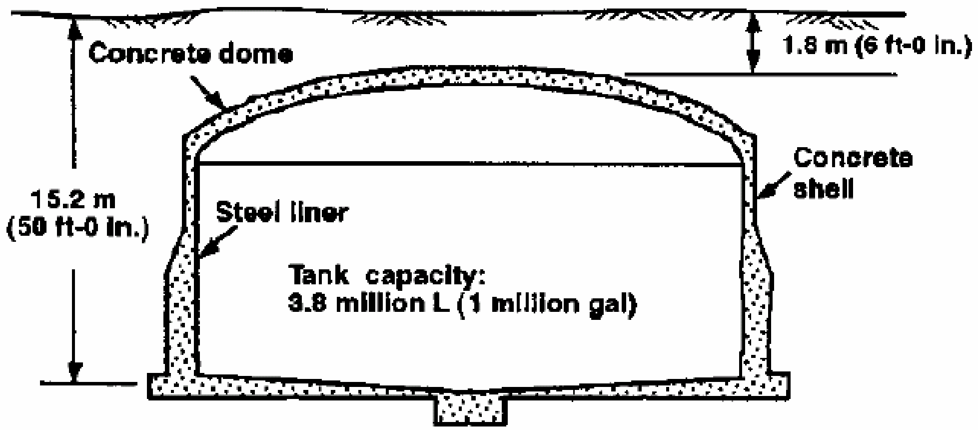
HLW Workshop
January 19-20, 2005

HLW Tank Example (Hanford)

Figure 2-3. Cross-Section of Single-Shell Tanks.



23-m (75-ft)-dia Single-Shell
Tank Farms: 241-A*, 241-AX*, 241-SX

* A and AX have flat bottoms

WHC-SD-TWR-RPT-002, Rev. 0-A

STRUCTURAL INTEGRITY AND POTENTIAL FAILURE MODES OF THE HANFORD HIGH-LEVEL WASTE TANKS

F. C. Han
Lockheed Martin Hanford Company, Richland, WA 99352

U.S. Department of Energy Contract DE-AC06-96RL13200

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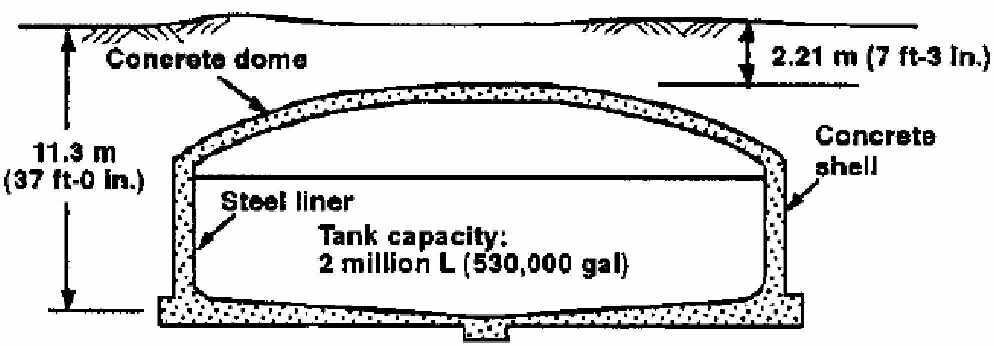


23-m (75-ft)-dia Single-Shell
Tank Farms: 241-B, 241-BX, 241-C,
241-T, 241-U

Site Specific Structural Problems

Large steel tanks containing radioactive waste are susceptible to extensive cracking caused by ground settlement, earthquakes, or accidents.

- *Nominally, 250 High Level Waste (HLW) Storage Tanks (some operating since 1950s)*
  - *304L or 347SS – INEEL*

    Wall thickness (t) range from 4.5 to 8.0 mm
  - *Carbon steel: A285Gr B, A516, A537 – Savannah River, Richland*

    Multiple designs t=12.7 mm for Type 1

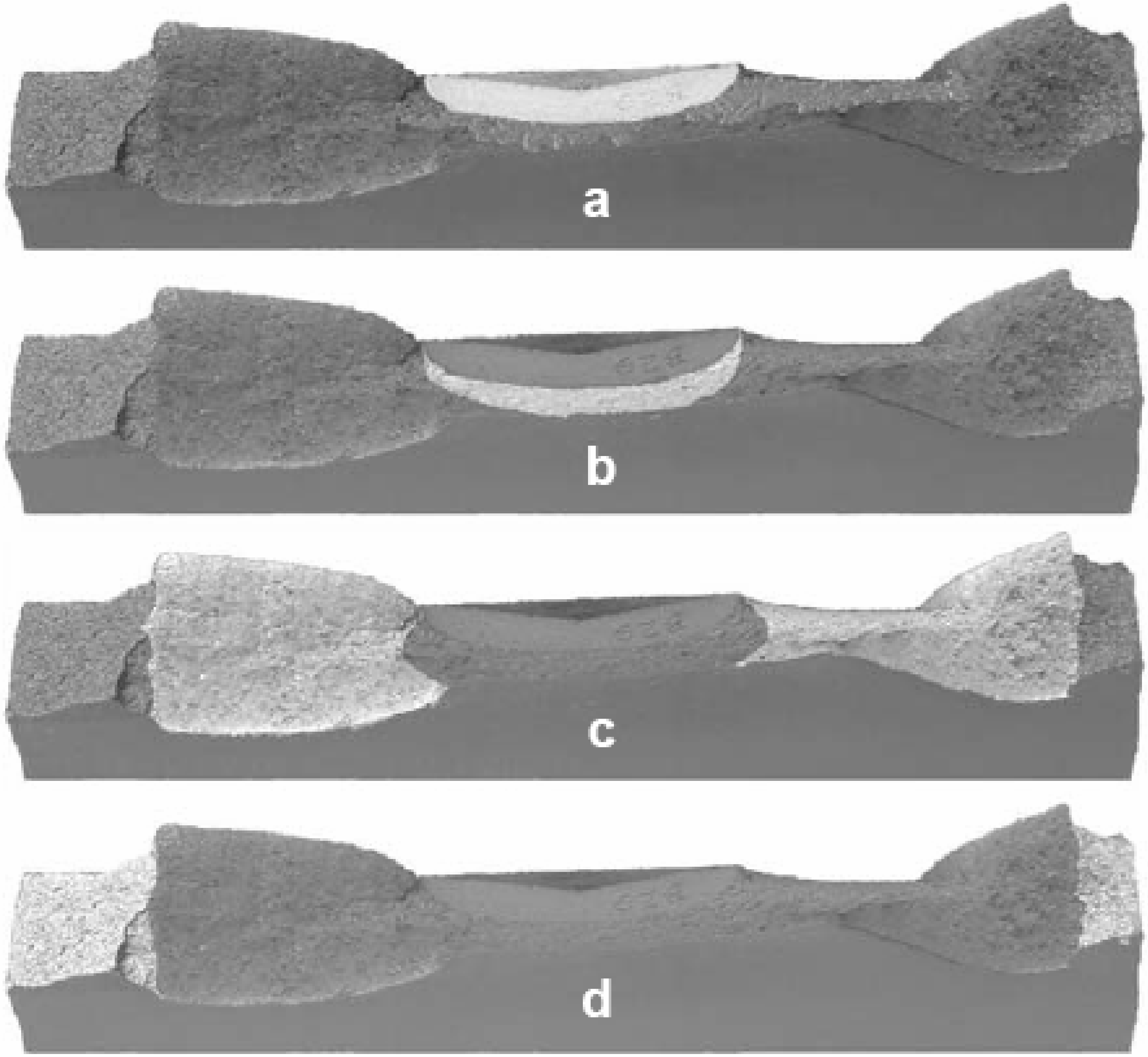
    t=15.9 mm for Type 2

    t=12.7 to 22.2 mm for Type 3
- *Environment:*
  - *Acid in SS tanks*
  - *Alkaline in carbon steel tanks*

Site Specific Structural Problems (Continued)

- *Loading condition*
  - *Normal operating – including waste retrieval*
  - *Design accident – earthquake, fluid sloshing*
- *Degradation (cracks and thickness reduction)*
  - *Corrosion – local/general*
  - *SCC*
- *Consequences of a Failure (only as related to fracture technology)*
  - *Safety of Workers and Public*
  - *Environmental*
  - *Adverse Publicity / Fear*

Problem Complexity



Scientific Concepts and Objectives

*Develop and validate fracture mechanics models to **predict** the fracture process for ductile materials in engineered structures.*

- *Initiation of crack growth*
- *Stable crack growth*
  - *Penetration of wall thickness*
  - *Growth in length (2c) direction*
- *Unstable cleavage cracking*

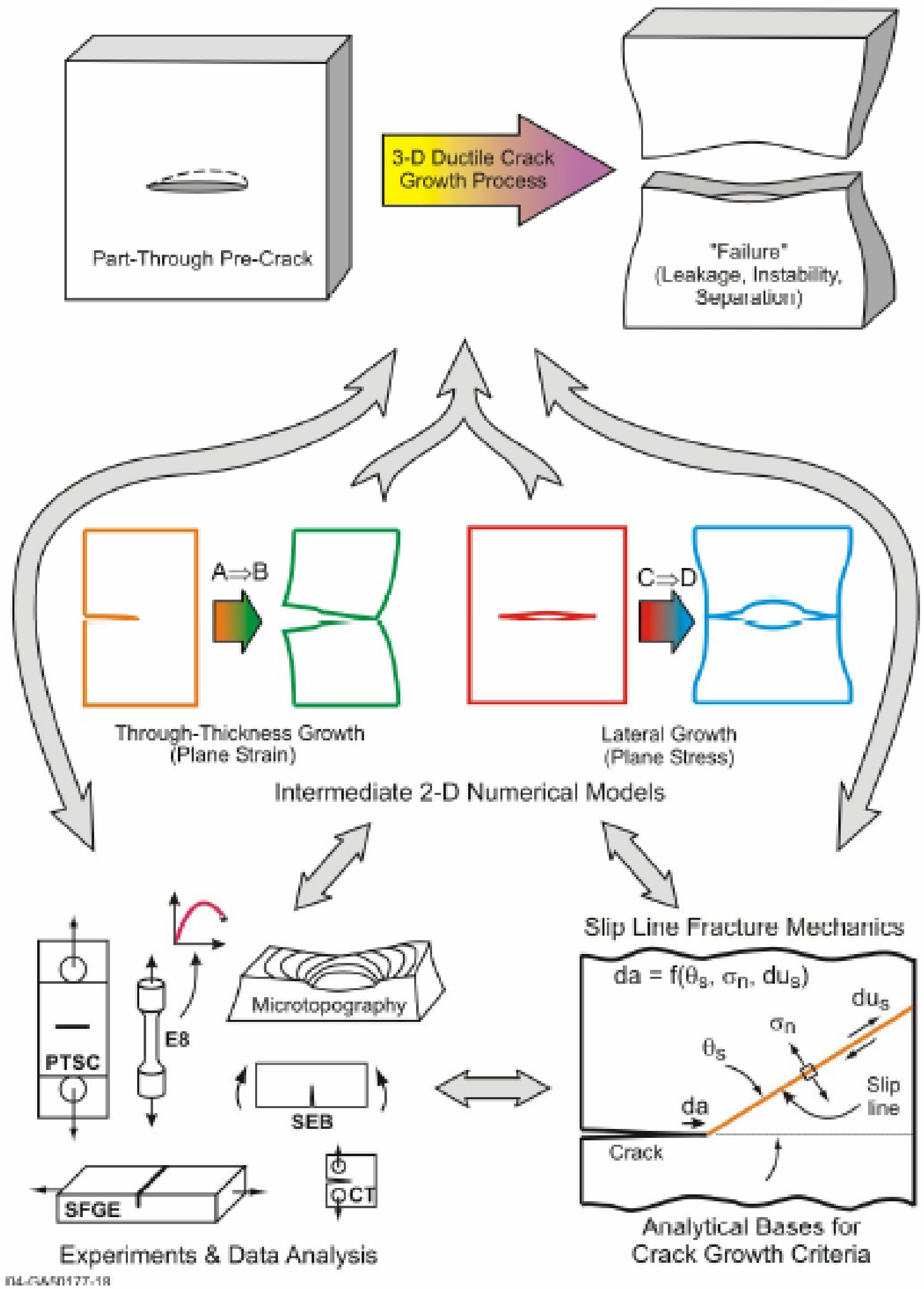
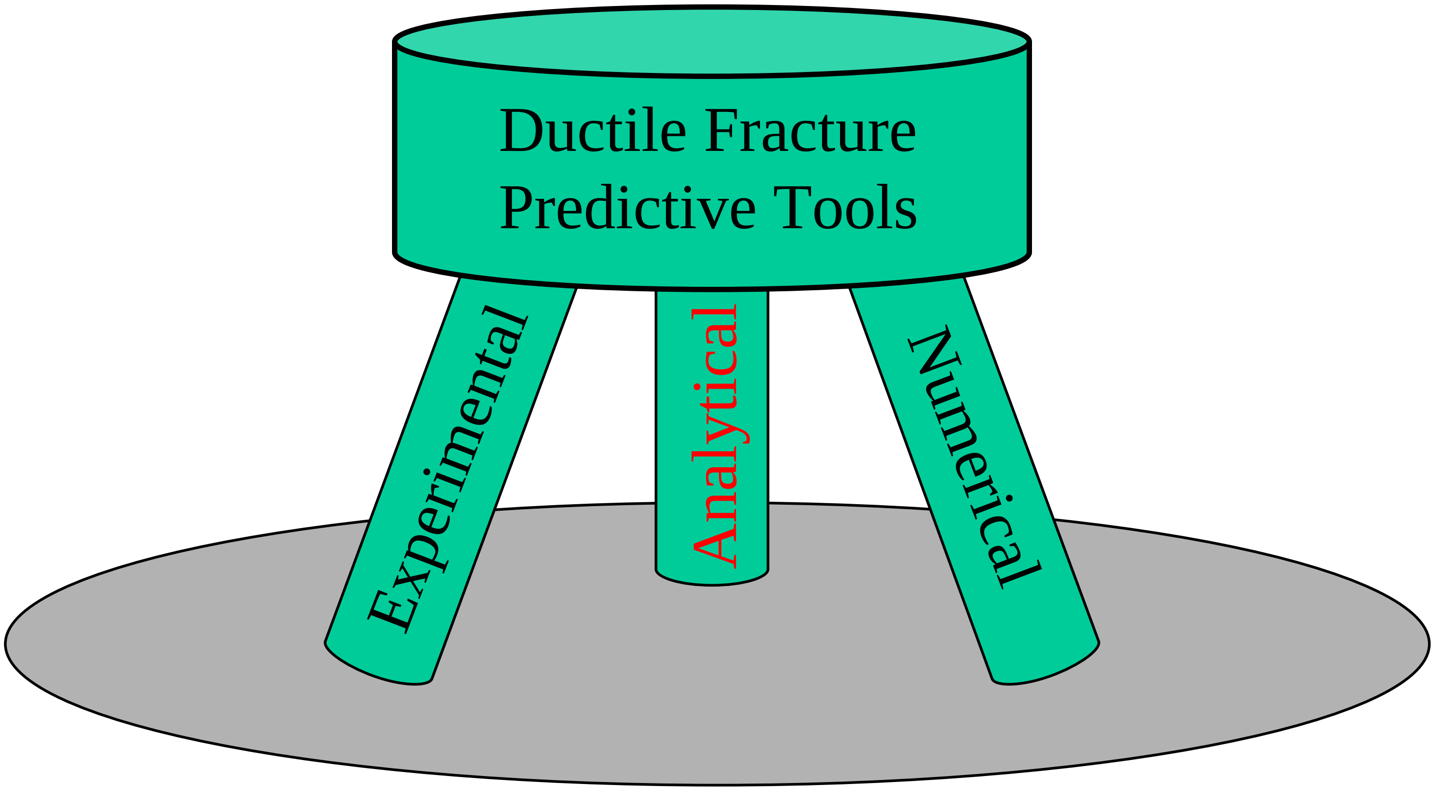


Figure 3. Flow diagram showing how experimental, analytical, and numerical activities relate and work synergistically towards a comprehensive, generalized 3-D numerical model of ductile crack growth.

Innovative Aspects

The People coupled with the Approach

• *E. D. Steffler, INL*	*Experimental/Numerical*
• *W. R. Lloyd, INL*	*Experimental*
• *F. A. McClintock, MIT*	*Analytical*
• *R. L. Williamson, INL*	*Numerical (Commercial Code)*
• *M. M. Rashid, UC Davis*	*Numerical (Research Code)*
- Mili Selimotic, UC Davis	*Graduate Student*


Ductile Fracture
Predictive Tools
Experimental
Analytical
Numerical

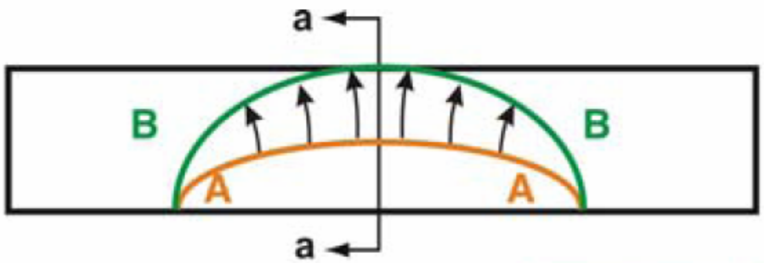
Analytical Objectives

In the analytical studies of this problem, we are focusing on two limiting conditions:

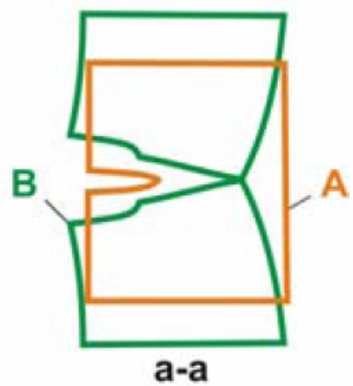
1. ***The plane strain growth of cracks through the wall of the tank.***
2. ***The lateral growth of through-cracks for many plate thicknesses in generalized plane stress.*** (Generalized plane stress means negligible stress in the thickness direction, but in ductile metals it means variable plate thickness from earlier crack growth.)

In both cases, we are considering the statistics of predicting rare transitions from the typical ductile, dimple mode of crack growth to the brittle, cleavage mode, using data from lower temperature tests.

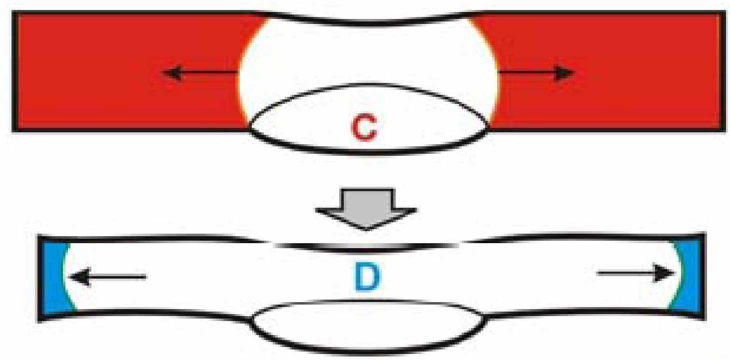
Crack Front Profile Progress



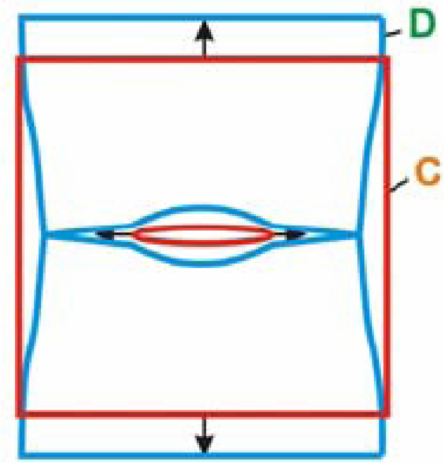
Growth stage A→B
Dominated by growth at section a-a; reasonably approximated by 2-D plane strain for initial development



Growth stage B→C
Transition regime. No critical behavior observed, and most complex to model. To be examined when functional 3-D model is available.



Growth stage C→D
Dominated by lateral growth, with slant fracture variation. Possible change from ductile to brittle.



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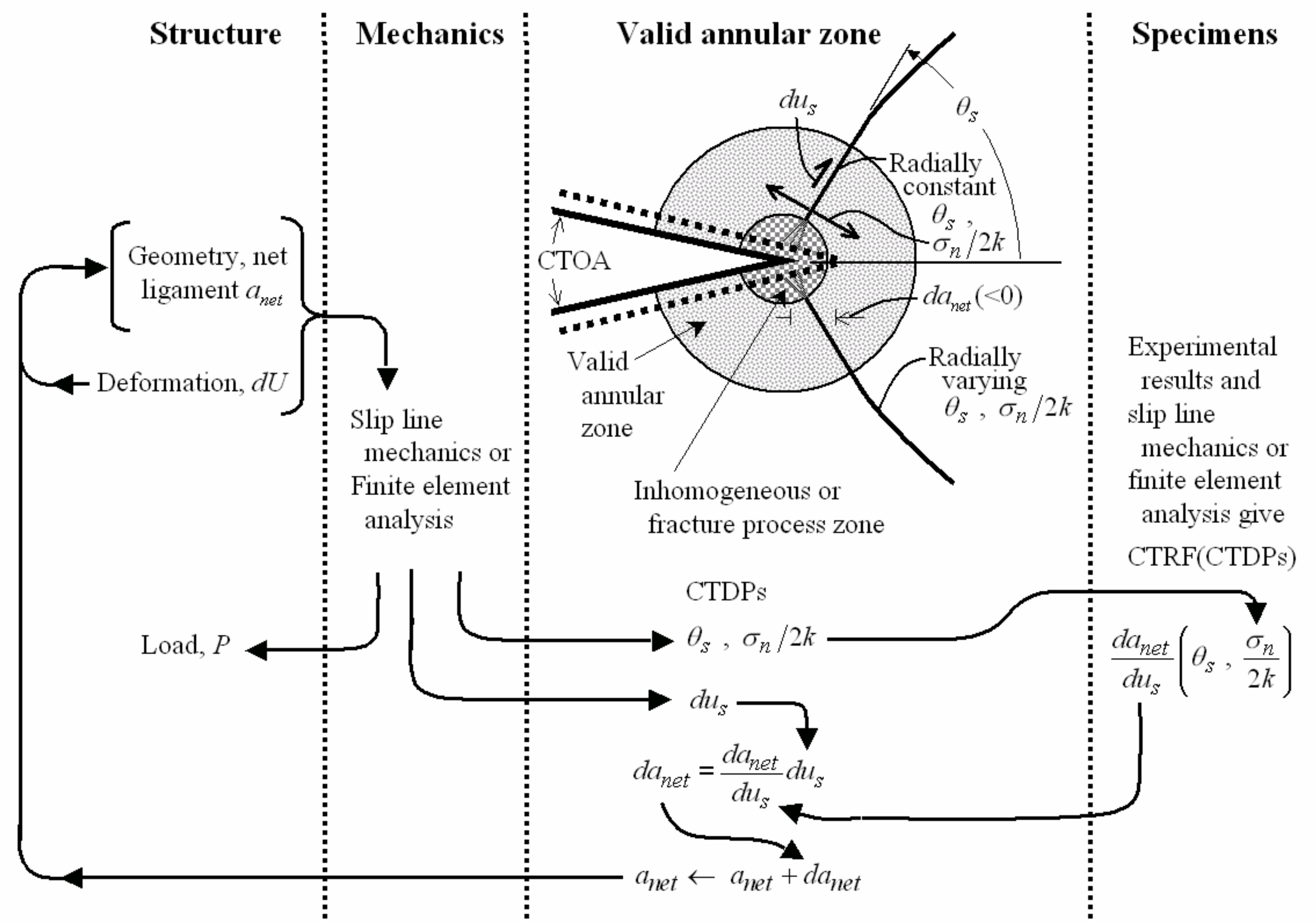
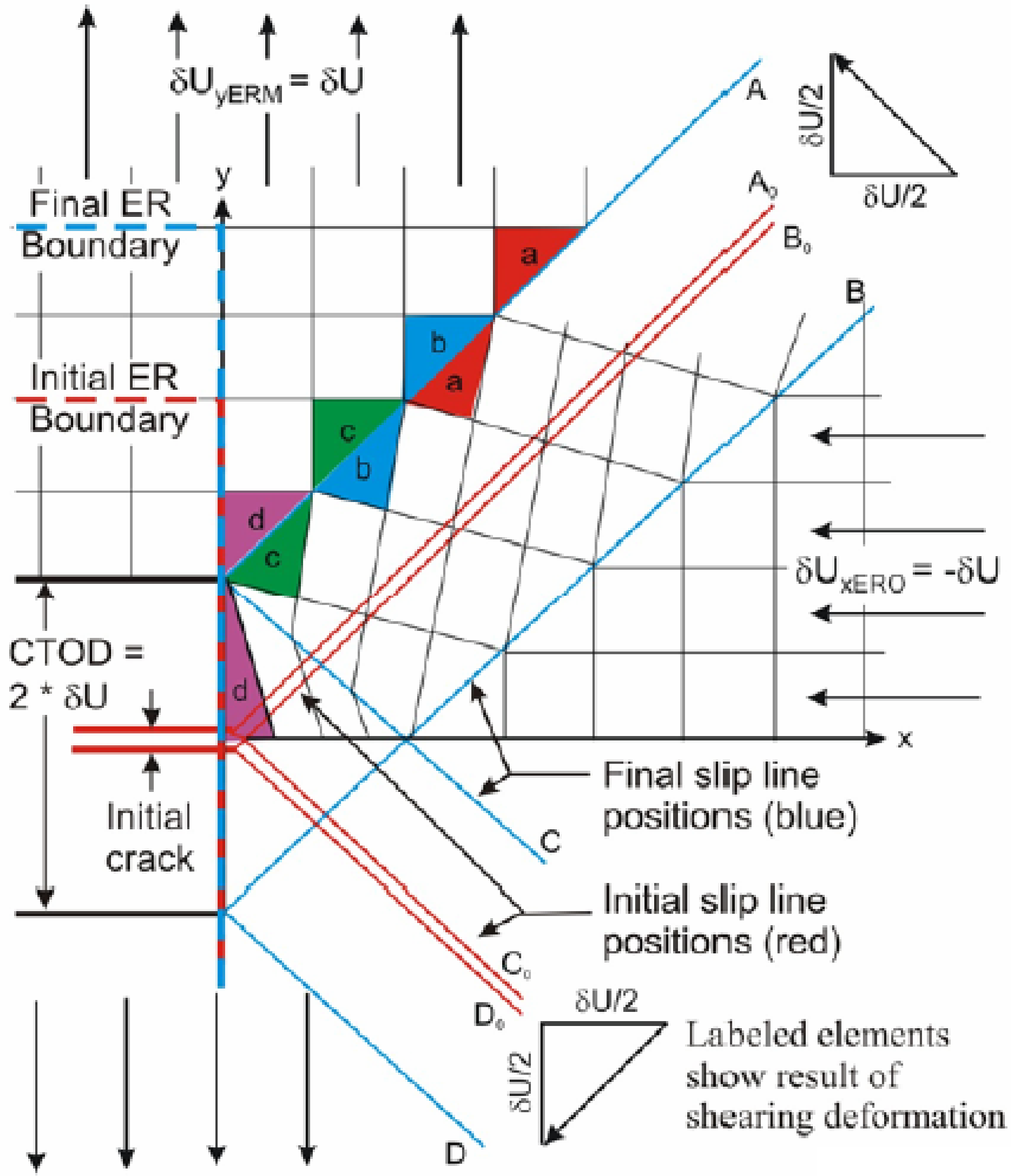
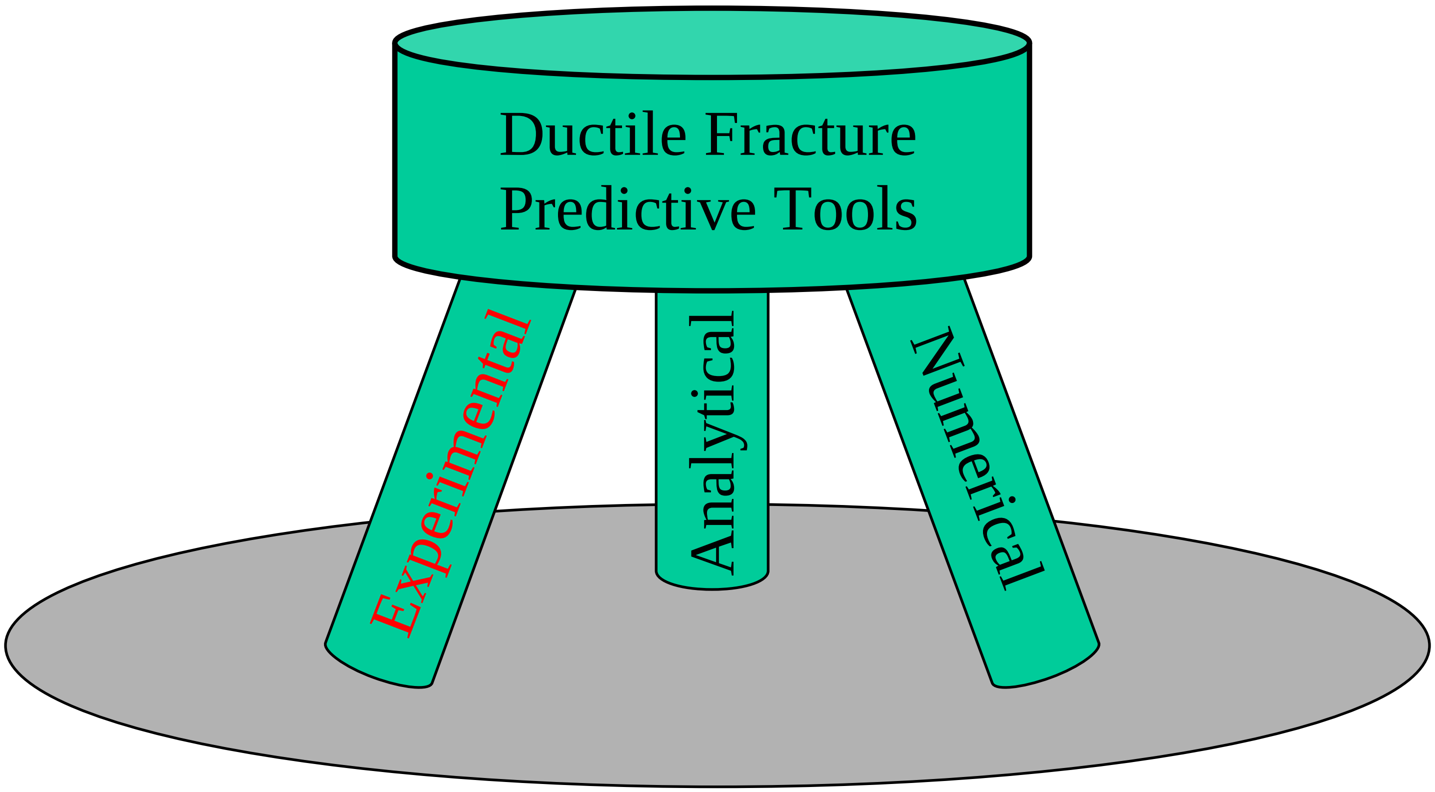
The Mechanics of Plane Strain Ductile Crack Growth



The process of fully plastic, plane strain, non-hardening, fracture mechanics.

SLFM Identified Parameters Used in FEM Comparisons




Ductile Fracture
Predictive Tools
Experimental
Analytical
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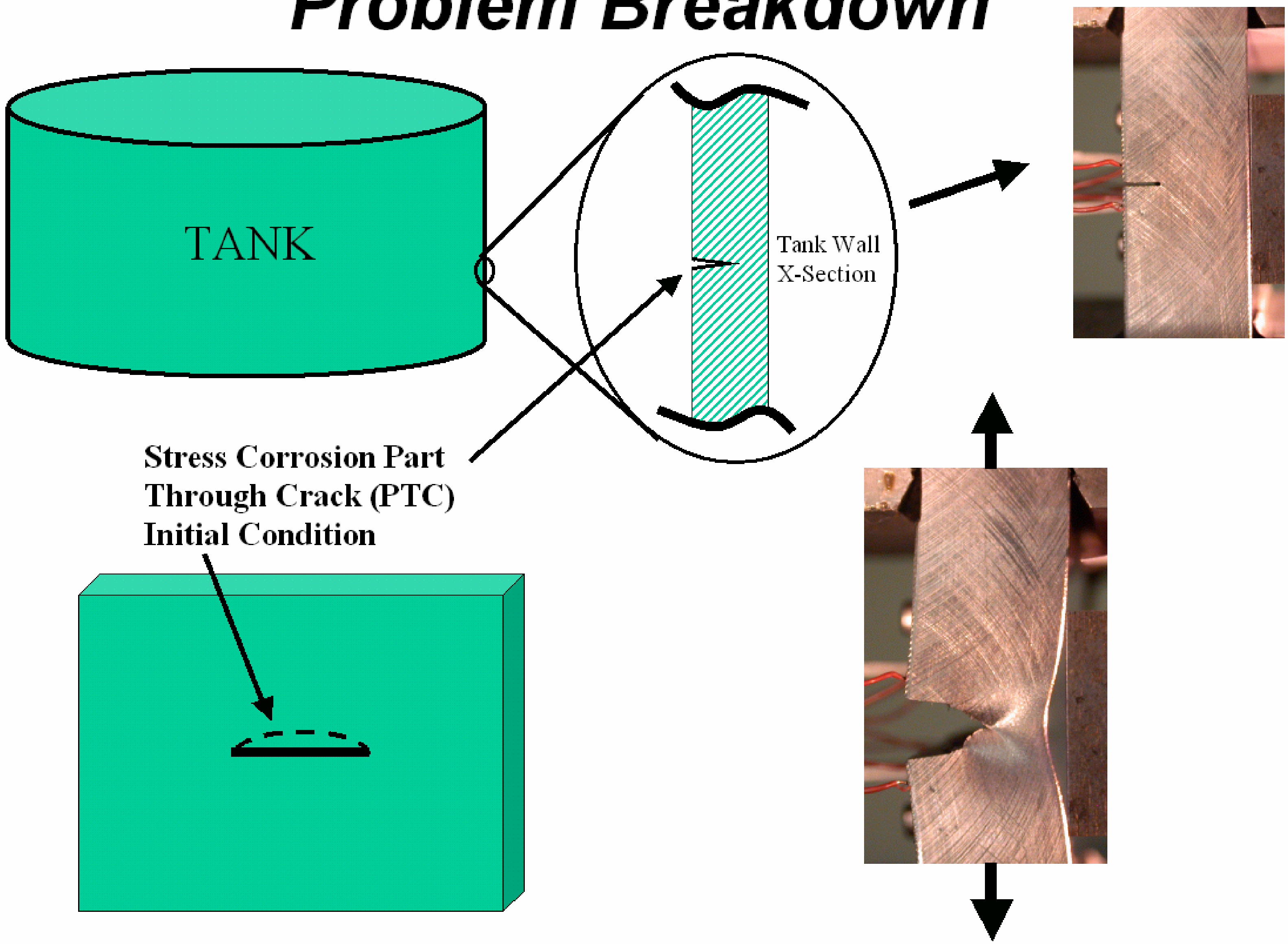
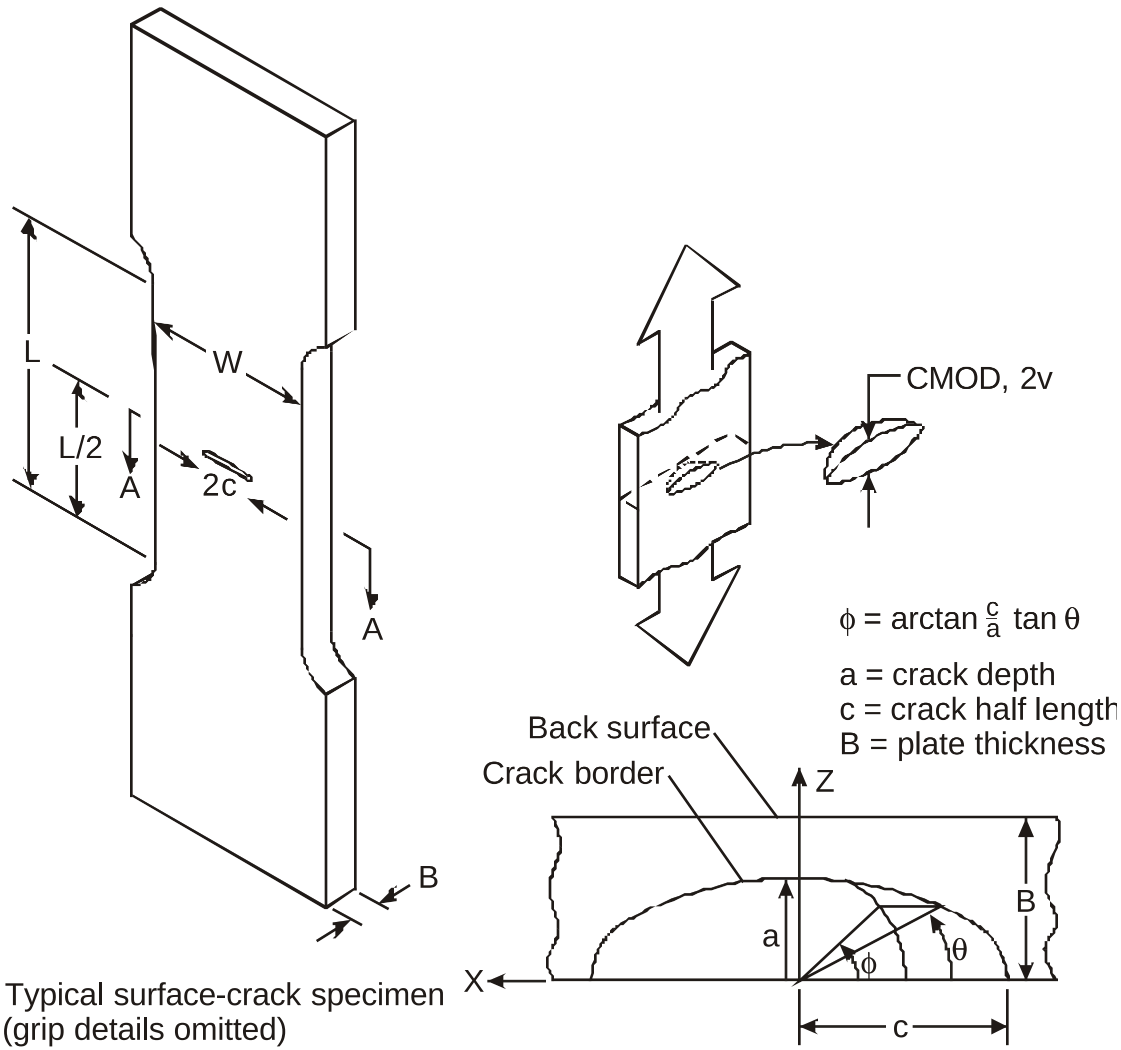
Problem Breakdown



Surface Crack Specimen Geometries

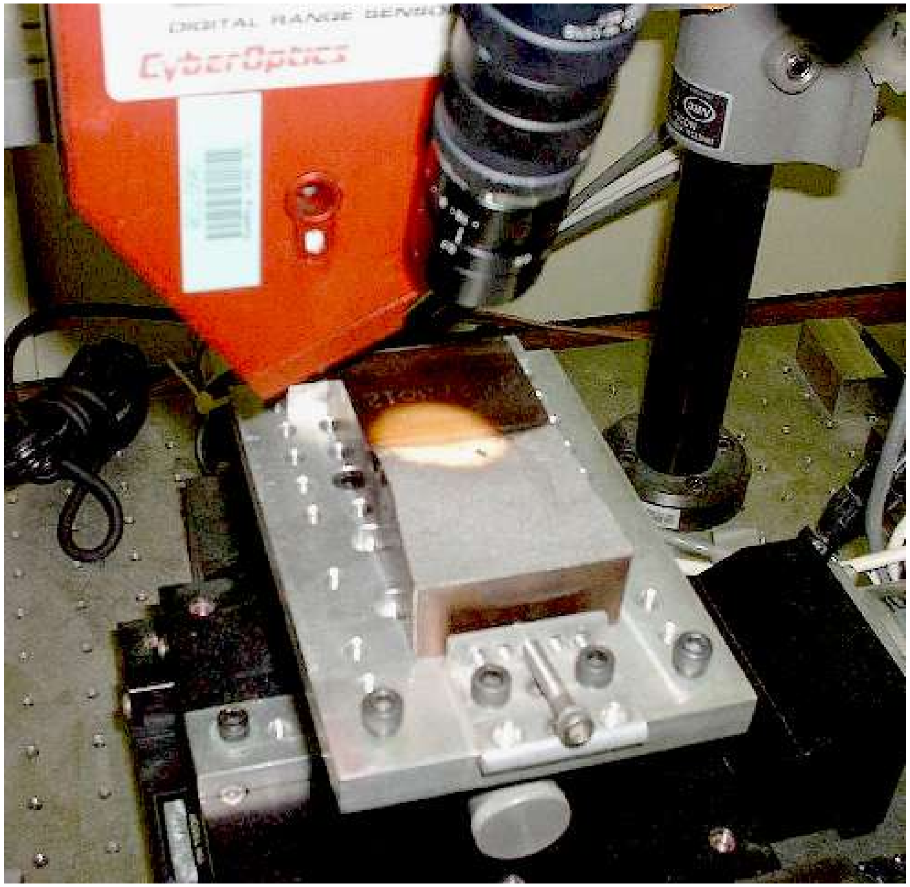


(a) Typical surface-crack specimen
(grip details omitted)

Section A-A

01-GAM0111-03

Microtopographic Analysis – Capabilities Overview



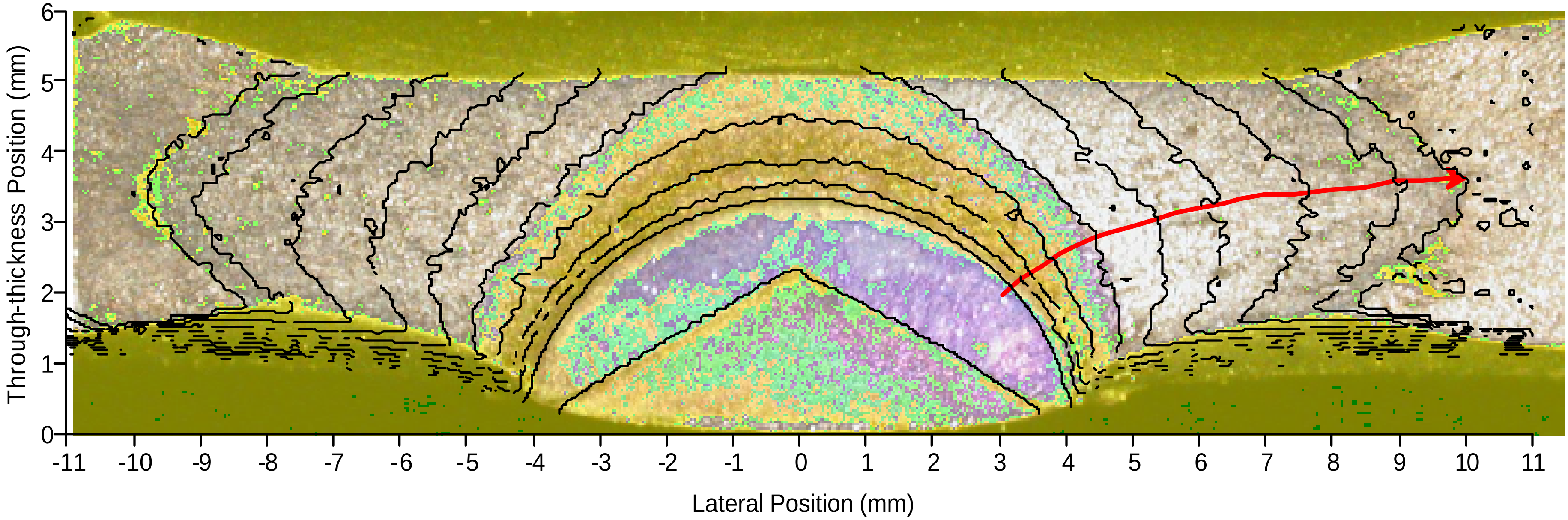
Microtopography scanning system collecting data from one of two opposing fracture surfaces from a large SE(B)-type specimen (B = 50 mm).

- Any ductile fracture process/event can be analyzed – test specimen or real structure
- All data collection and analyses occur AFTER the crack growth has happened
- Micron spatial resolution
- All ductile fracture CTRFs can be extracted – CTOD, CTOA, etc.

References:

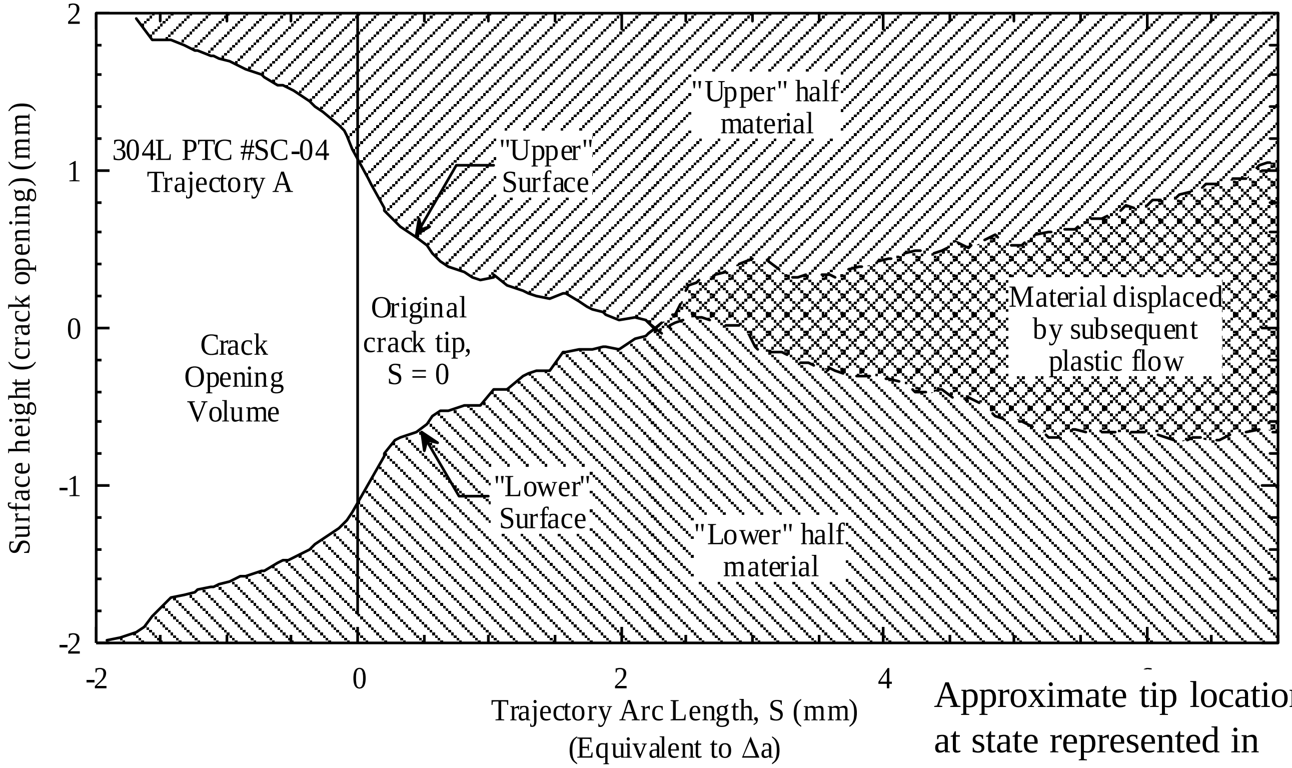
- Lloyd, W.R., "Microtopography for ductile fracture process characterization – Part 1: Theory and methodology," **Engrg. Frac. Mech. 70**, pp.387-401, 2003.
- Lloyd, W.R. and McClintock, F.A., "Microtopography for ductile fracture process characterization – Part 2: Application for CTOA analysis," **Engrg. Frac. Mech. 70**, pp.403-415, 2003.
- Lloyd, W.R. et al., Microtopographic Analysis of Part-Through Crack Growth in Alloy 304L Plate-type Tension Specimens, **INEEL/EXT-03-00495**, 2003.

Whole-field Analysis of Incremental Crack Growth



- Contour lines represent incremental crack front positions at crack tip opening increments of 0.5 mm* (overlaid on actual fracture surface picture)
- Purple dye region shows crack front position at point of through-thickness penetration, and confirms accuracy of microtopographic analysis (note excellent correlation of crack front position contour with dye-stained area boundary)
- Fracture surface contrast change marks end of ductile tearing during test – again note excellent correlation of microtopographic prediction of crack tip position
- Gradient analysis of these data provide a whole-field directional CTOA map

*last contour increment is 0.2 mm, not 0.5, corresponding to CTOD = 4.2 mm



Available Info

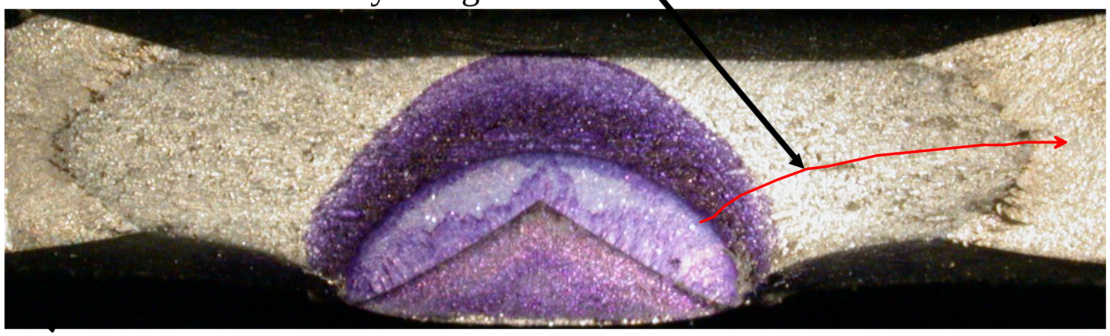
- CTOD$_i$
- CTOA vs. Δa
- Local CTOA vs. Δa
- CMOD vs. Δa
- ΔCTOD vs Δa
- ΔCTOA vs. Δa
- Φ* vs. Δa
- …others

*Φ is the crack tip "zig-zag" angle, or instantaneous growth Direction.

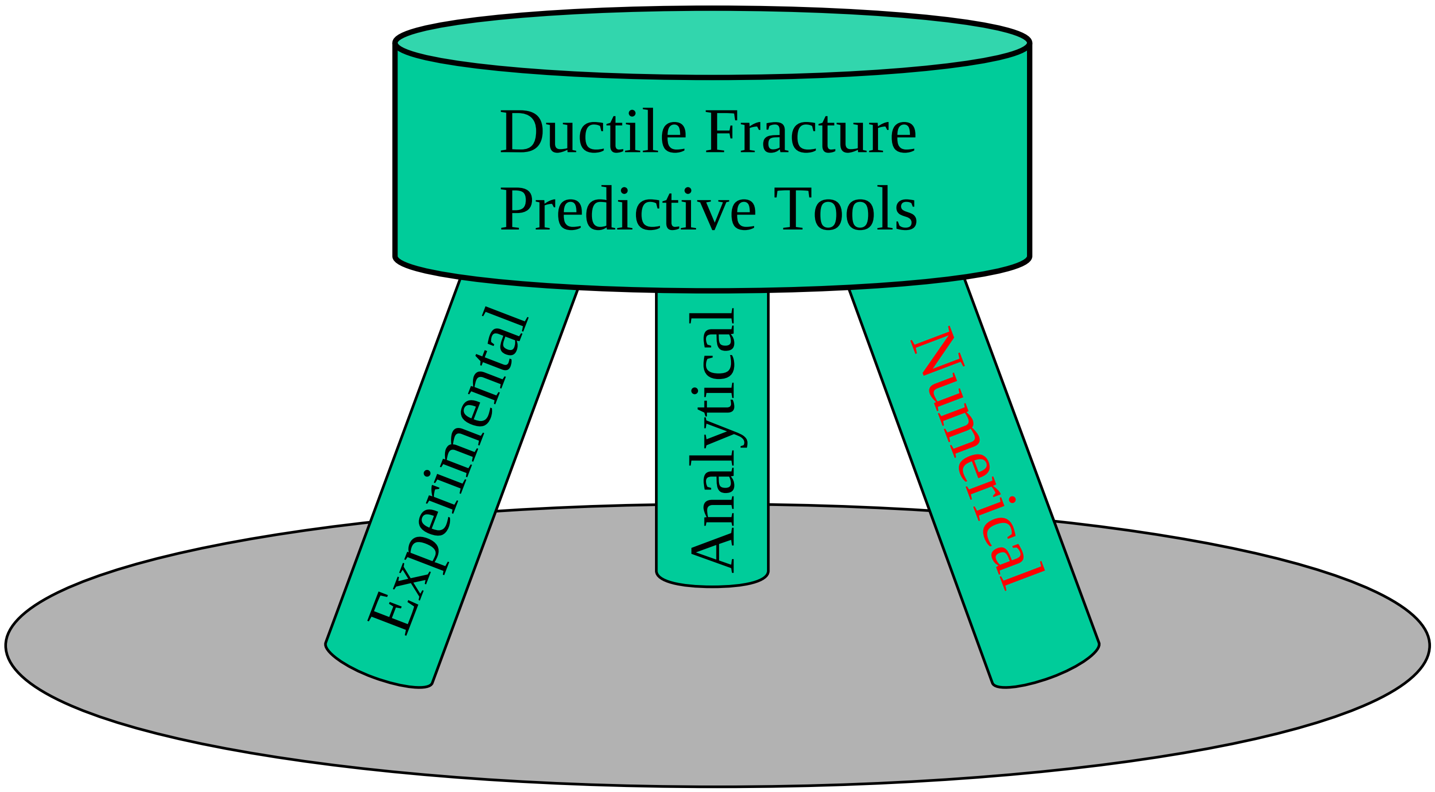
Approximate tip location at state represented in analysis figure above

Trajectory Detail Analysis Snapshot

- Any trajectory can be analyzed
- Data from a family of trajectory analyses are combined to provide a complete 3-D representation of ductile surface crack growth, including all parameters at every state of the fracture process.



"Lower" half fracture surface – red line is crack growth Trajectory A


Ductile Fracture
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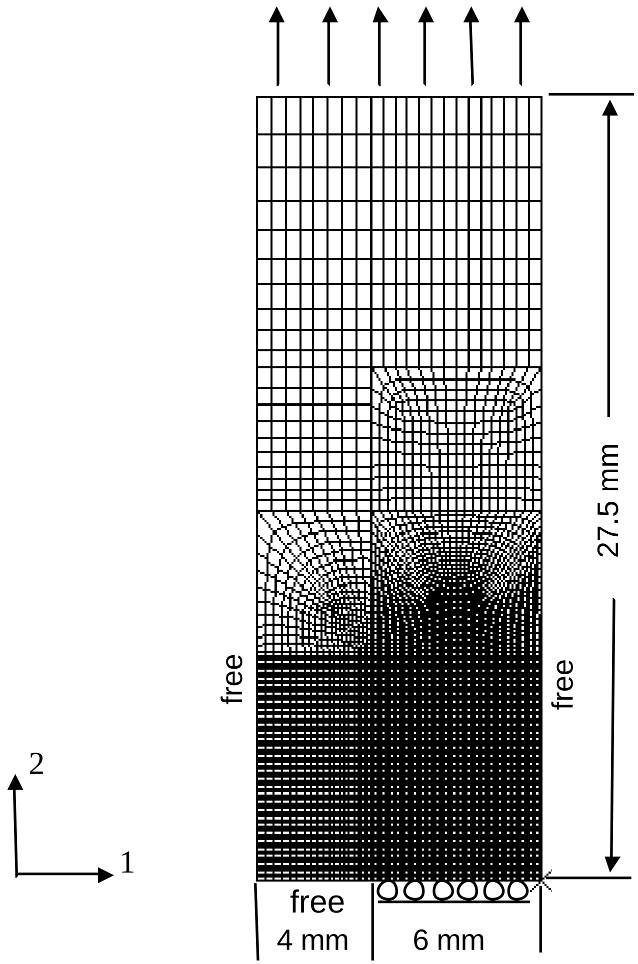
Computational Modeling of Ductile Fracture: Finite Element Node Release

- Crack extension is achieved by node release along a predefined path
- Release is governed by the Crack Tip Opening Angle (CTOA) at a prescribed distance from the tip along the crack flank
- Initial conceptual testing and model verification has been performed for a simple plane strain extension specimen



Node Release Model: Investigation of Key Numerical Parameters

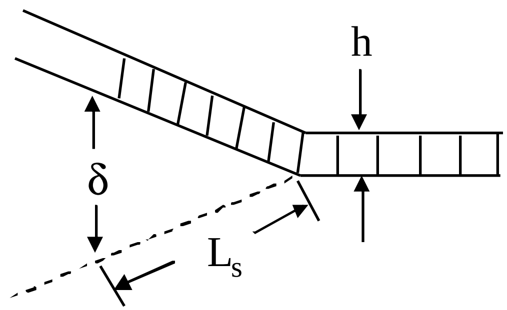
- Key numerical parameters have been investigated by sensitivity study and comparison to analytical solutions

  - mesh size (h) near crack extension region

  - local CTOA geometry (L_s, δ)

  - traction reduction rate at node release

  - debond tolerance

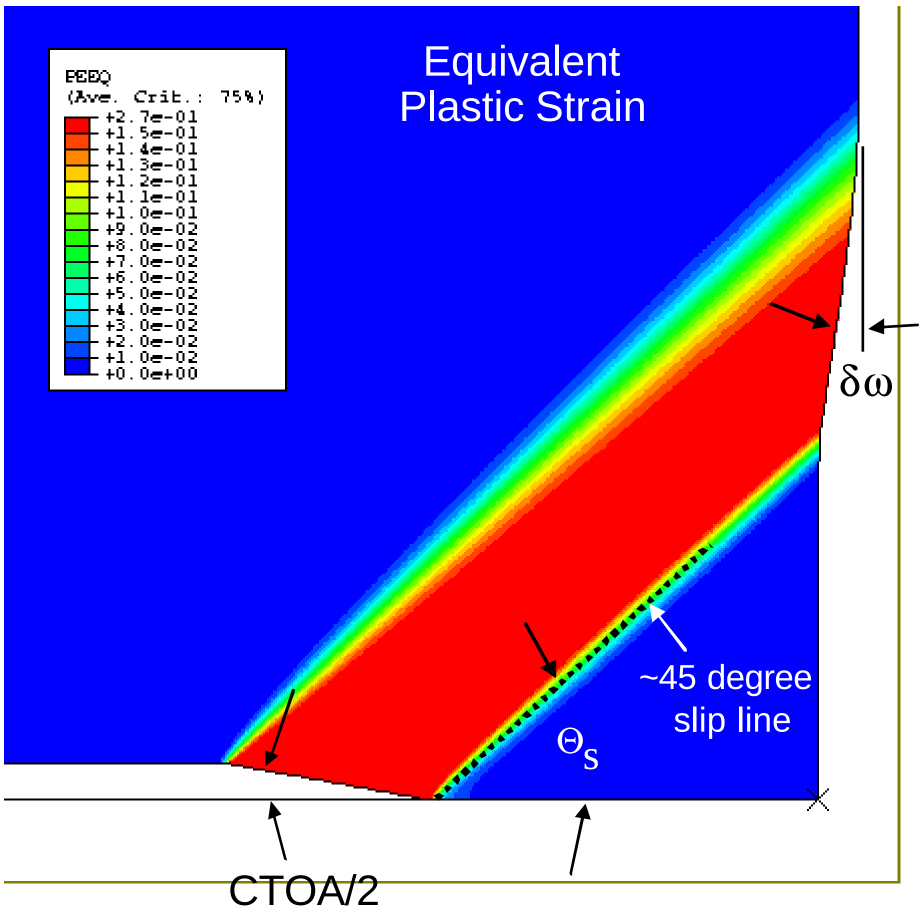


- Investigation has provided improved understanding of:

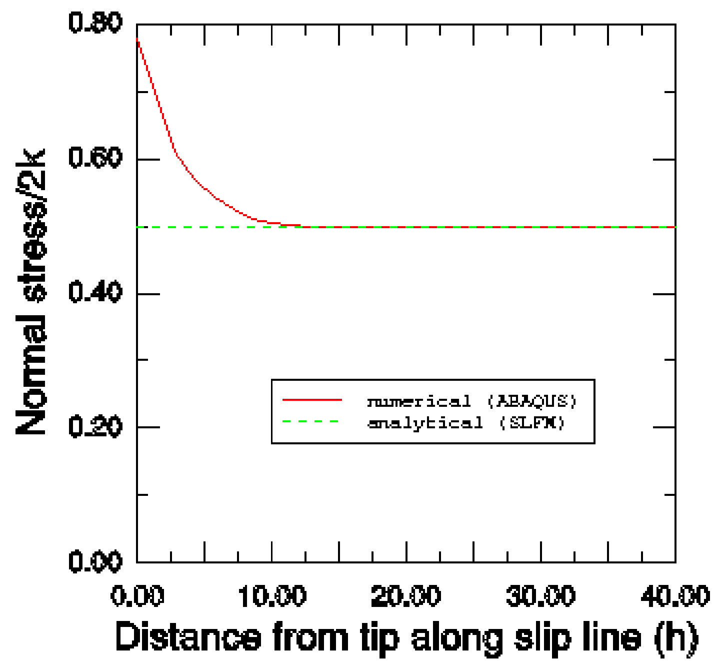
  - tradeoffs between numerical accuracy and efficiency

  - appropriate numerical parameters to achieve reliable solutions

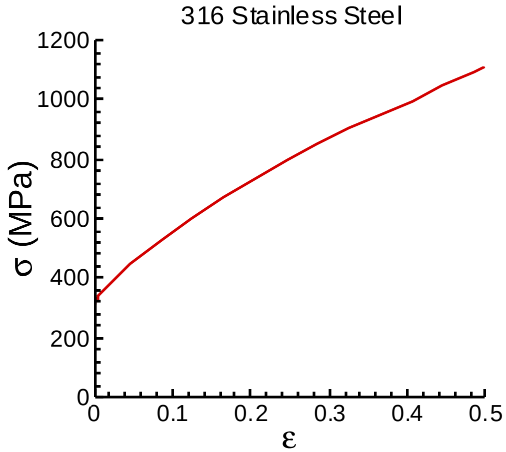
Node Release Model: Verification by Comparison to Analytical Solution

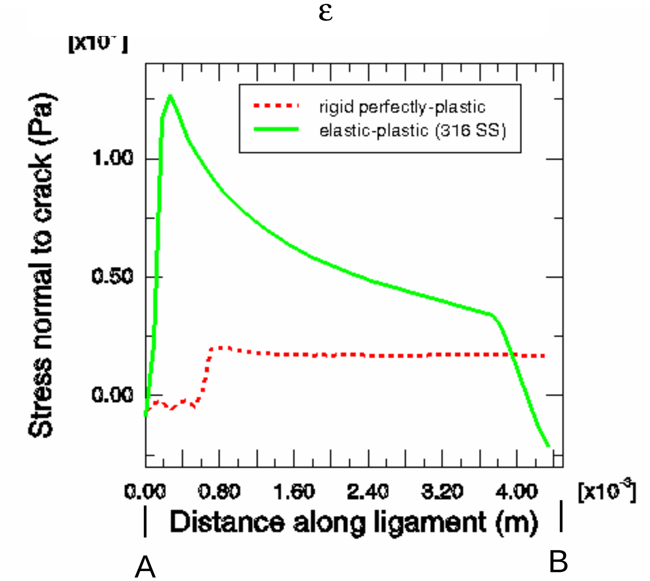


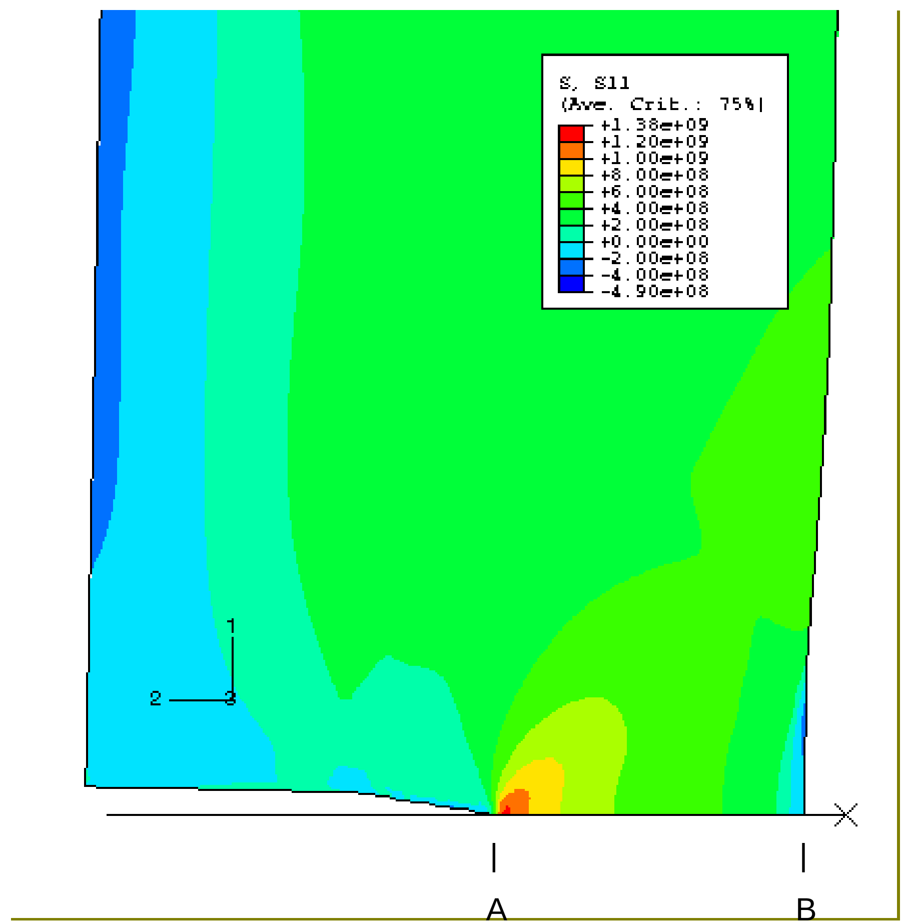
	Analytical (SLFM)	*Numerical (FEM)*
CTOA	20	19.95
Θ_s	45	43.5
$\delta\omega$	7.43	7.68



Node Release Model: Application to Isotropic Hardening Material







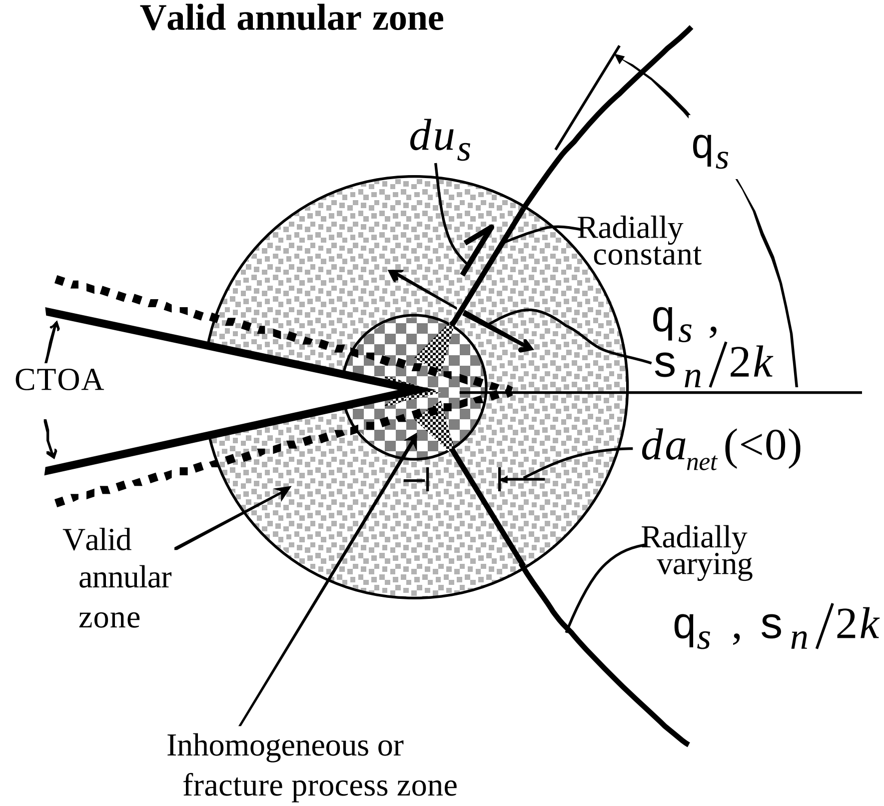
Node Release Model: Developing Improved Predictive Capability

- From SLFM (McClintock)

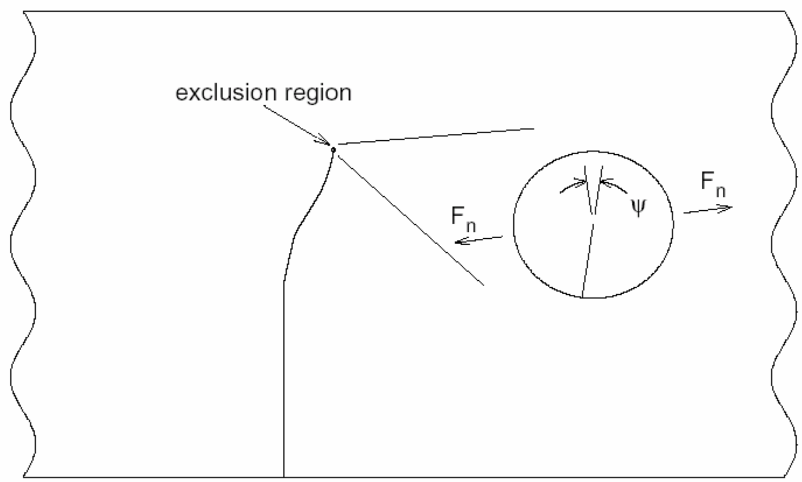
$$\text{CTOA} = f\,(\theta_s, \sigma_n/2k)$$

- ABAQUS user subroutines, currently under development and testing, will permit control of crack extension parameters (e.g. CTOA) based on crack tip driving parameters (e.g., θ_s, σ_n) at locations distant from the crack tip so finite element size and material inhomogeneity have negligible effect.

Valid annular zone



Computational Modeling of Ductile Fracture: Exclusion Region Theory

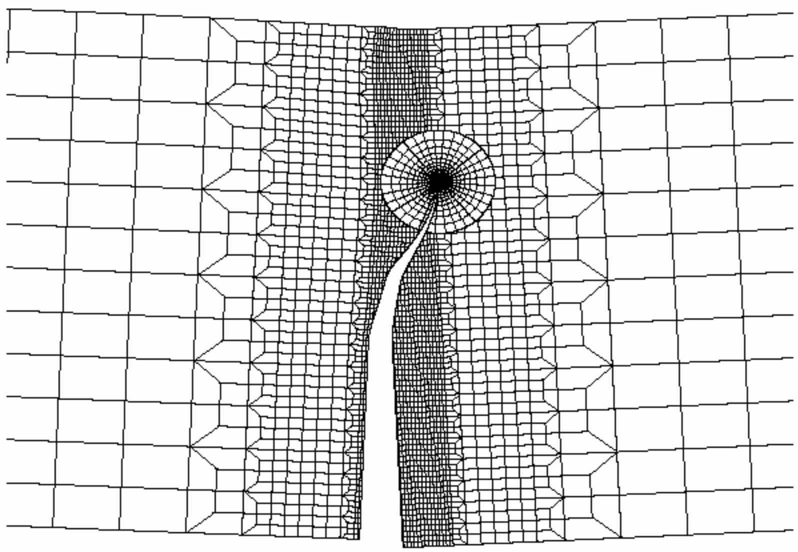


A *separation function* $\Phi(\psi)$ is used to define the fracture criterion:

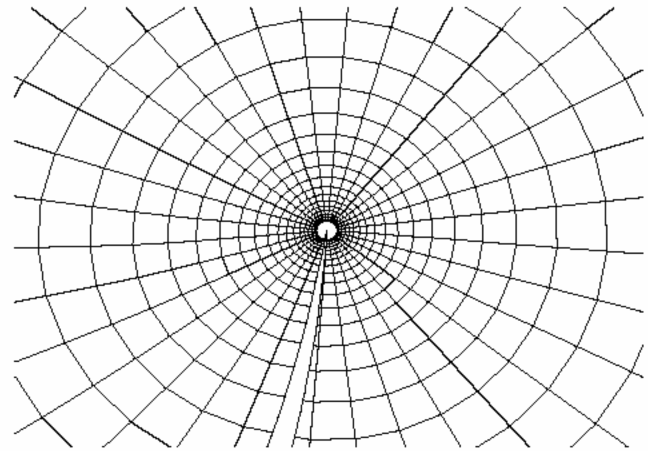
$$\Phi(\psi) = \frac{\bar{F}_n}{\pi a^3} \int_{ER} \varepsilon_p \, \mathrm{d}a \,, \quad \bar{F}_n = \frac{< F_n >}{\sup \{F_n\}} \,, \quad F_n = \int_{\psi}^{\pi} \mathbf{M} \cdot \hat{\mathbf{t}}(\theta) \, a \, \mathrm{d}\theta$$

Crack advances so that $\Phi(\bar{\psi}) \leq \Phi_c$, and in the direction $\bar{\psi}$ that maximizes $\Phi(\psi)$.

Implementation of Exclusion Region Theory



deformed mesh detail showing moving mesh "patch"



mesh patch with ER at the center

- The separation functional form can be anything while the critical parameter is a material dependent parameter experimentally determined.
- Provided with fully functional 2-D research code.
- Working to implement approach in 3-D to adequately address remaining challenges.

INL

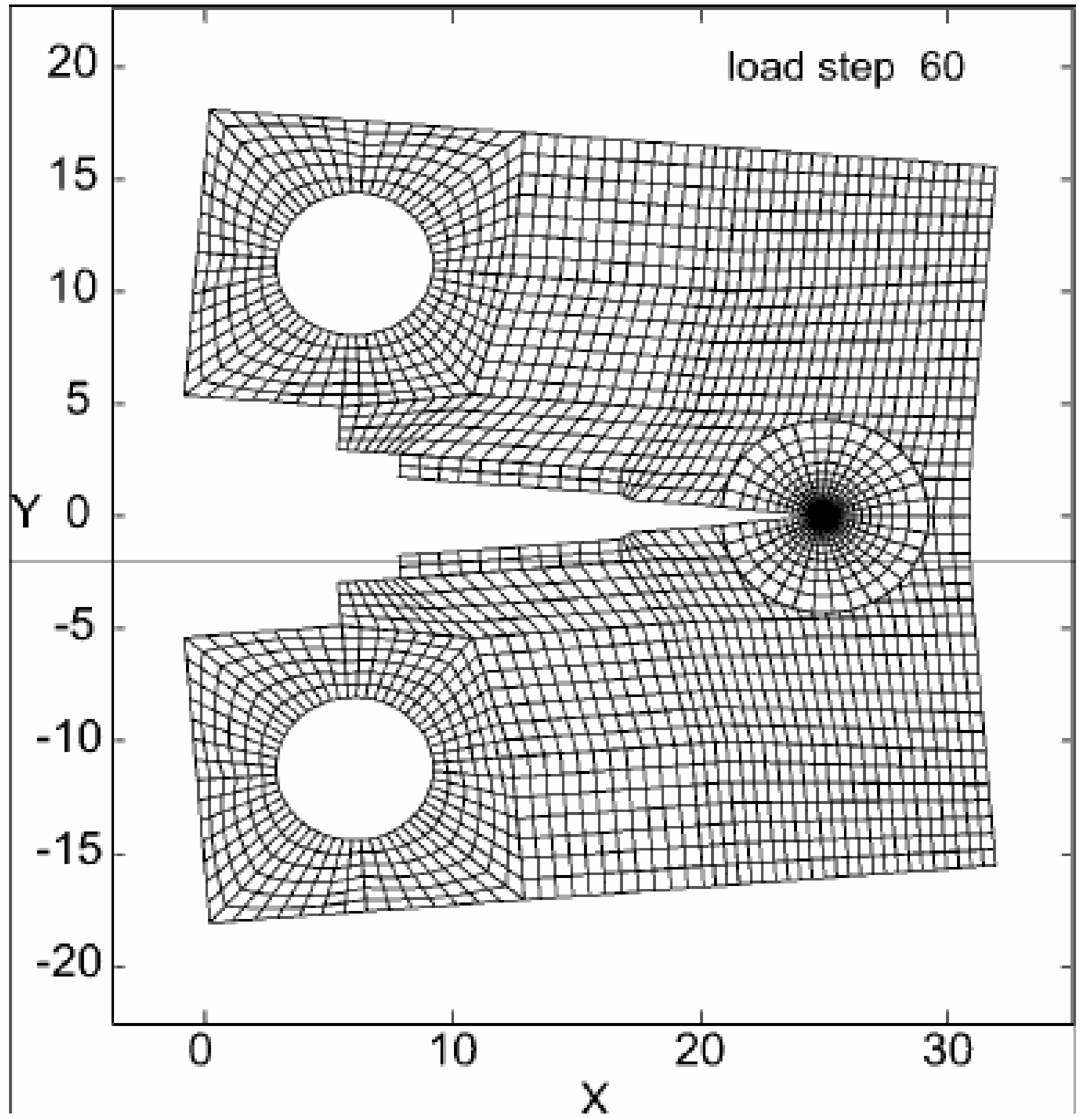
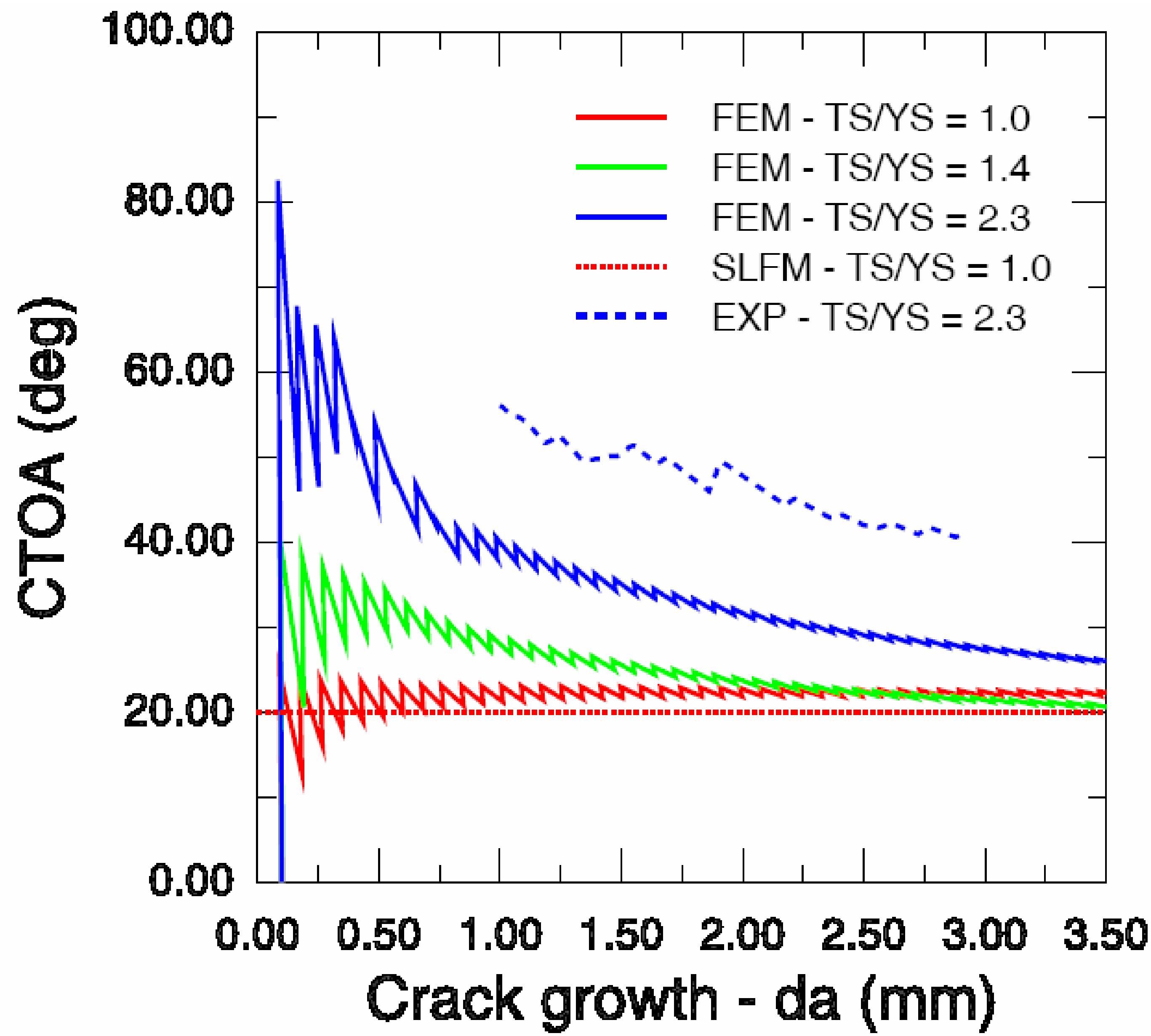


Figure 10 Deformed mesh from a 2-D FEFRAC ductile crack growth analysis. This analysis corresponds to a compact-tension test of A710 steel conducted at the INEEL.

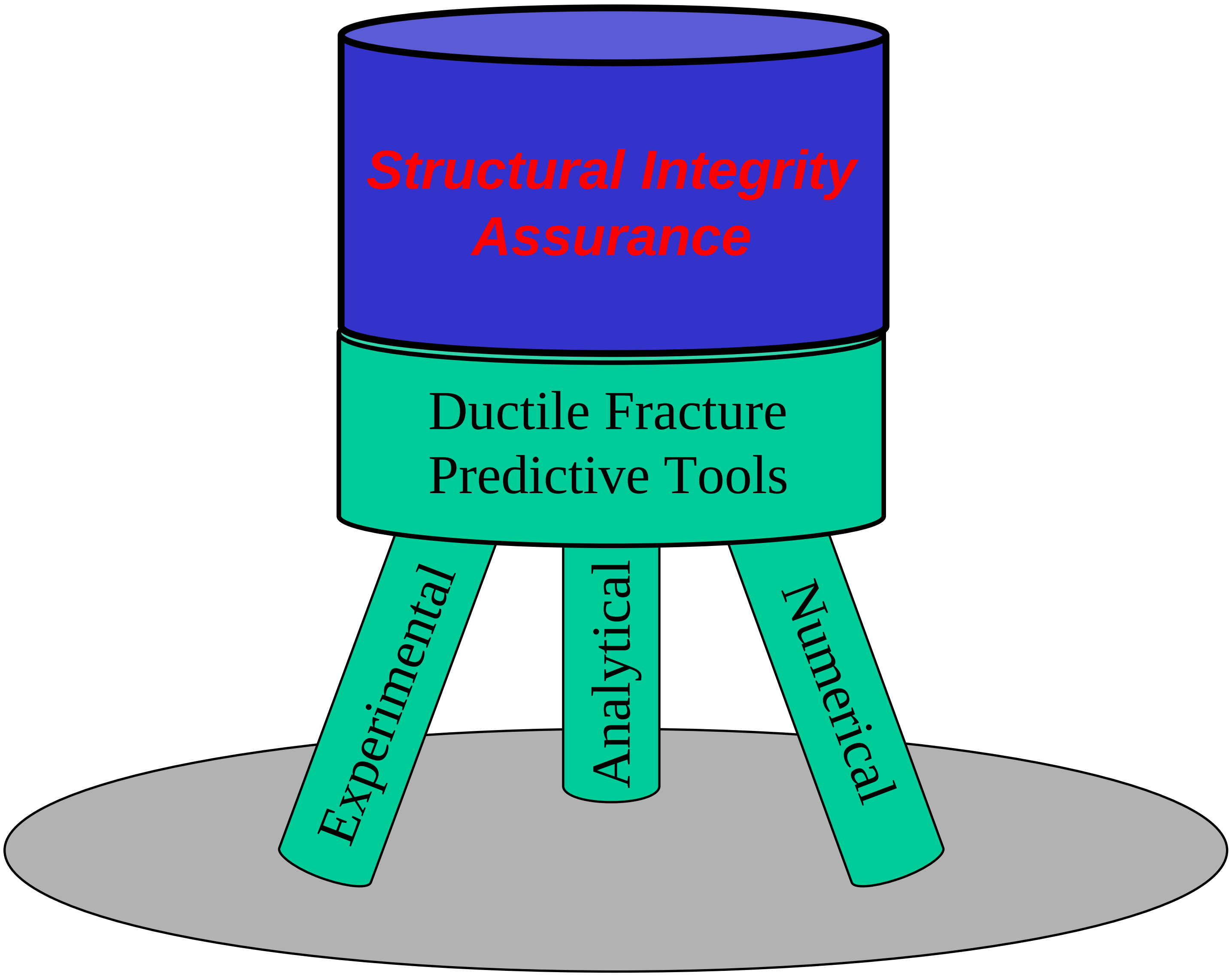
INL



100.00
80.00
60.00
40.00
20.00
0.00
CTOA (deg)
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
Crack growth - da (mm)
FEM - TS/YS = 1.0
FEM - TS/YS = 1.4
FEM - TS/YS = 2.3
SLFM - TS/YS = 1.0
EXP - TS/YS = 2.3

Future Scientific Directions and Plans *INL*

- *Continue to use concepts of slip-line fracture mechanics (SLFM) in FEM setting - ductile crack growth criterion guide laboratory experimentation.*
- *Use the ER theory of fracture with SLFM motivated separation function to capture complex fracture behavior of real ductile metals.*
- *Complete work on powerful, fully 3-D computational platform - complex nonlinear problems involving crack extension. Two major enabling innovations unique to this research program.*
- *Exploit the innovative measurement and diagnostic techniques developed at the INL to validate ER-based fracture model. This approach will avoid simplifying idealizations that characterize other research efforts in ductile fracture, and which substantially diminish their technological usefulness.*


Structural Integrity Assurance
Ductile Fracture Predictive Tools
Experimental
Analytical
Numerical

In Conclusion…

We have team members that:

- *understand* the technical challenges
- have a great deal of *interest* in working towards viable solutions to the real-world application
- have worked on *related problems* (structural integrity, lifetime extension, novel numerical approach)
- have a great deal of *relevant experience*

Our team is working at the leading edge of ductile fracture predictive technology.

Acknowledgements and Contact Information

U.S. Department of Energy Basic Energy Sciences and Environmental Management Science Program

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